BACK

1. DEVELOPMENT OF DESIGN RELATIONS

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The design relations discussed in this chapter were developed from physical principles, experience, and laboratory data. They represent a semiempirical dominant process model which is internally consistent and well suited for use as a design tool. Because the relations represent a semiempirical simplification of a complex process, the limits imposed by the simplifying assumptions and the data base will be discussed, even though these limits will seldom be approached in design problems. The procedure for applying the relations to design problems is described in chapters 3 and 4.

FLOW RESISTANCE

Flow resistance of an open channel is a result of viscous and pressure drag over its wetted perimeter. For a vegetated channel, this drag may be conceptually divided into three components. They are (1) the sum of viscous drag on the soil surface and pressure drag on soil particles or aggregates small. enough to be individually moved by the flow (soil grain roughness), (2) pressure drag associated with large nonvegetal boundary roughness (form roughness), and (3) drag on the vegetal elements (vegetal roughness). Since these forces act directly on the moving fluid in opposition to the local velocity vector, it is equally valid, and sometimes more convenient, to discuss the flow-boundary interaction in terms of the energy expended in moving the fluid against each component force rather than directly in terms of the component forces. Whichever approach is taken (both will be used in the discussions which follow), the conceptual division remains the same, and the key to understanding the flow behavior is recoqnizinq that the flow and the boundary interact. Neither may be-considered entirely independent of the other when considering flow resistance or channel stability.

Interaction of the boundary with the flow field causes the effective boundary roughness of a grass-lined channel to become a function of flow conditions. Flow resistance coefficients that are treated as constants under changing flow conditions for rigid boundary applications will, therefore, not remain constant for the case of a grass boundary. This will be true for any of the flow equations traditionally used in hydraulic applications.

The flow equation that will be used throughout this handbook is Manning's equation, which may be written as:

$$V = \frac{1.49}{n} R^{2/3} S^{1/2}$$

in which V = the mean velocity at the cross section in feet per second,
R = the hydraulic radius in feet,
S = the energy slope at the cross section, and
n = Manning's resistance coefficient.

This equation was selected for use here primarily because of its widespread acceptance for open channel applications involving both rigid and natural boundaries.

Velocity Profile

For most grass-lined channels, drag on the vegetal elements dominates the flow resistance. Correct interpretation of flow resistance behavior therefore requires an understanding of the interaction of the flexible vegetal elements with the flow field.

Ree (1949) identified three distinct flow regions that become apparent when flow resistance for a given channel is plotted against depth or discharge. The apparent behavior of the velocity profile, as illustrated in figure 1.1 for each of these regions, is further discussed by Temple (1982). For the very low flows represented by figure l.la, the depth of flow is less than the deflected grass height and the local velocity is primarily dependent on the local vegetal density. Increases in flow depth less than that required to overtop the veqetation cause little change in mean velocity. Therefore, the flow resistance expressed in terms of traditional parameters such as Manning's n will tend to increase with increasing depth or charge. Since the mean flow velocity at any cross section is directly related to the percentage of the cross section blocked by vegetal elements and the uniformity of their spacing, type of vegetation and qualíty of stand would be expected to dominate any resistance function for this region.

For the intermediate flows represented by figure l.lb, the flow depth is greater than the deflected height of the grass. The vegetal elements tend to align themselves with the flow and exhibit a waving action. This waving action appears to continue as a result of turbulent interaction (lift and drag fluctuations associated with turbulence) long after structural hinge points have developed in the elements. Leaf structure becomes less important as the elements become better aligned with the flow. Increases in flow depth in this region result in a decrease in the thickness of the boundary zone dominated by vegetal action and an associated large increase in mean velocity. Therefore, flow resistance expressed in terms of Manning's n decreases with increasing depth or discharge. The vegetal parameters expected to dominate the resistance function under these conditions are the number of stems[1] and the length of each which drags in the flow. Stem diameter and stiffness would be expected to exert a secondary influence.

For the large flows represented by figure l.lc, the depth of flow is much greater than the deflected height of the vegetation. As the depth increases and thickness of the boundary zone approaches a minimum, the portion of the flow passing through the vegetation becomes negligible compared to that flowing above, and the flow resistance of the grass expressed in terms of Manning's n tends to be a constant. Since the minimum boundary zone thickness depends primarily on the bulk of the material present and the growth characteristics of the vegetation near the bed, these variables would be expected to dominate the flow resistance function in this region.

Most practical problems related to stability design of grass-lined open channels concern flows in the intermediate-flow range. Discharges less than those required to submerge the vegetation seldom will generate significant sustained erosion, and stability limits are generally exceeded before the boundary zone thickness becomes negligible. The intermediate-flow range will, therefore, be assumed in the following discussions. Because reliable physically based resistance relations are not readily available for the very high or low flows, a constant value of Manning's n equal to its value at the nearest mathematically specified boundary (see eq. 1.2a) is usually assumed when an estimate outside the intermediate flow range is required. Although this may represent the best estimation available, the preceding discussion demonstrates that this approach will fail to recognize the proper dominant variables. This is particularly true for the very low flows.

Retardance Relations

When consideration is limited to the intermediate-flow region, Ree and Palmer (1949) showed that for given cover and boundary conditions, Manning's n could reasonably be expressed as a unique function of the product of mean velocity and hydraulic

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[1] The term "stem" is used here to identify those vegetal elements that act relatively independently in the flow. This will usually correspond reasonably well to a layman's definition of a stem. Stem length is measured from the point of contact with the soil to the stem tip.

radius.[2] The "n-VR" curves presented by the SCS (1954) are expressions of this functional relationship obtained by graphically fitting the available data.

A reanalysis of the data by Temple (1980, 1983) resulted in the general retardance relation given by:

$$n_R = \exp\{C_I(0.0133[ln(VR)]^2 - 0.0954 ln(VR) + 0.297) - 4.16\} \quad (1.2)$$

with the limits of the intermediate flow range approximated by:

$$0.0025\ C_I^{2.5} \leq VR \leq 36 \quad (1.2a)$$

where n_R = a reference value of Manning's resistance coefficient applicable to vegetation established on relatively smoothly graded fine-grained soil,
CI = the retardance curve index describing the retardance potential of the vegetal cover,
and V and R are as previously defined.

As indicated in the previous section, the vegetal flow resistance in the region of interest is primarily a result of drag along the entire length of the submerged stems, which have become more or less aligned with the flow. Analysis along these lines leads to an equation relating the empirical retardance curve index to measurable vegetal parameters given as (Temple 1982):

$$C_I = 2.5\,(h\sqrt{M})^{1/3} \quad (1.3)$$

in which h = the representative stem length in ft, and
M = the average stem density in stems per square foot.

This approach works well for grasses with well-defined stems, but becomes more difficult to apply for more brushy or branching vegetation such as alfalfa. Further discussion and design aids related to curve index parameter estimation are given in chapter 3.

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[2] More detailed analysis shows that the relation may be slightly improved by expressing n as a function of Reynold's number VR/ν. However, the uncertainty in the variables defining the vegetal cover is such that the improvement becomes statistically insignificant. Analysis based on the assumption of a constant kinematic viscosity is, therefore, considered justified.

To be consistent with the stress/energy balance assumptions to be discussed in the following section on effective soil stress, the component roughnesses expressed in terms of Manning's coefficient are related to each other and to the reference value n_R as (Temple 1980):

$$n = \sqrt{n_s^2 + n_\Psi^2 + n_v^2} \qquad (1.4a)$$

which, for the data base of equation 1.2 reduces to:

$$n_R = \sqrt{(0.0156)^2 + 0^2 + n_v^2} \qquad (1.4b)$$

yielding the general relation:

$$n_R = \sqrt{n_R^2 + n_s^2 + n_\Psi^2 - (0.0156)^2} \qquad (1.4c)$$

where n = Manning's coefficient for the channel under the specified flow conditions.
n_s = Manning's coefficient associated with soil particles of a size capable of being detached by the flow at stability-limiting conditions (soil grain roughness).
n_Ψ = Manning's coefficient associated with boundary roughness elements other than vegetation which cannot be detached by the flow (boundary form roughness).
n_v = Manning's coefficient associated with the vegetation (vegetal roughness).

The constant 0.0156 in equation 1.4 is equal to the soil grain roughness for the fine-grained soils represented in the data base from which equation 1.2 was derived. Because large deviations of n_s and n_Ψ from their base values of 0.0156 (fine-grained soil) and 0.0 (prepared soil boundary resulting in negligible form roughness) are generally incompatible with the uniformity of cover required for an effective grass lining, variations in these parameters may often be ignored in the estimation of flow resistance. This allows equation 1.4c to be simplified to $n = n_R$ ($n_R^2 >> n_\Psi^2$; $n_R^2 >> n_s^2 - (0.0156)^2$). The error associated with this simplification will often be less than that associated with the estimation of the vegetal parameters required for the determination of n_R.

The definition of the grain roughness given above is somewhat more exacting, and the definition of form roughness more general, than those in common use. These definitions are, however, the ones appropriate for application of the concepts to channel stability or sediment transport computations and are consistent with the discussions introducing these concepts into the literature (Einstein 1950). The treatment of grain roughness as a soil property is not inconsistent with these definitions, providing consideration is limited to conditions near incipient channel failure.

Momentum and Energy Coefficients

Closely related to the flow resistance behavior of the lining are the momentum and energy coefficients required for correct application of conservation principles. These coefficients are defined by the relations:

$$\alpha = \frac{\int v^3 dA}{V^3 A} \tag{1.5}$$

and

$$\beta = \frac{\int v^2 dA}{V^2 A} \tag{1.6}$$

Where α is the energy (Coriolis) coefficient, β is the momentum (Boussinesq) coefficient, v is the velocity at a point, dA is a differential area, and the integration is carried out over the cross section. Discussions of the general significance and application of these coefficients are in most texts on open channel flow.

For most open channel flow problems involving channels of regular cross section, the deviation of α or β from unity is relatively small, and the error in computed specific energy or specific force based on setting the coefficients equal to unity is within the uncertainty of the other variables involved. Although the available data for grass-lined channels is extremely limited, an examination of the velocity profiles shown in figure l.lb shows that this is not true for the typical grass-lined channel condition. McCool (1970) reported observed values as high as 5 for the energy coefficient in an asymmetrical triangular channel lined with bermudagrass.

The importance of a coefficient of this magnitude may be seen by considering its influence on the Froude number, which is computed by the relation (Chow 1959):

$$F = \frac{V}{\sqrt{g \frac{A}{T} \frac{\cos\theta}{\alpha}}} \tag{1.7}$$

where F is the Froude number, g is the gravitational constant, θ is the bed slope angle, T is the channel width at the water surface, and the other variables are as previously defined.

Temple (1986) showed that the coefficients could be reasonably estimated by approximating the velocity profile by a constant velocity through the vegetal boundary zone and a modified Prandtl logarithmic velocity distribution above the boundary zone. Although this profile approximation is not acceptable for analysis of stress distribution involving the first derivative of the profile, it seems adequate for the problem of coefficient determination which involves only integrals of the profile.

The results of applying this approximation to two-dimensional (wide channel) flow conditions are presented in a curve fit form suitable for computer computations (lines 5090 through 5320 of appendix B, section 7) as:

$$c = 1+\exp\left\{ \{a_{4,3}\ \mathit{ln}(S)+\sum_{i=0}^{3} a_{i,3}\ C_I^{\,i}\}\ \mathit{ln}(X)+ \sum_{j=0}^{2} \{a_{4,j}\ \mathit{ln}(S)+\sum_{i=0}^{3} a_{i,j}\ C_I^{\,i}\}\ X^{j} \right\} \qquad (1.8)$$

where c is the coefficient (either α or β), and X maps the interval of equation 1.2a onto the interval [O,l] through the relation:

$$X = \frac{\mathit{ln}(q)\ -\ \mathit{ln}(0.0025\ C_I^{2.5})}{\mathit{ln}(36)\ -\ \mathit{ln}(0.0025\ C_I^{2.5})} \qquad (1.9)$$

where q is the volumetric discharge per unit width in cubic feet per second per foot. The required coefficient matrices are presented in tables 1.1 and 1.2. The curve fit relations are applicable for values of X between 0 and 1, slopes from 0.001 to 0.20, and curve index values greater than 2.0.

For channels where the two-dimensional flow assumption is not acceptable, reference values of the coefficients are determined by assuming two-dimensional flow in a channel having a flow depth equal to the maximum depth in the actual cross section. The energy coefficient is then found by multiplying the reference value by the three-fourths power of the ratio of the mean velocity which would exist for the two-dimensional channel to the actual computed mean velocity (for example application, see appendix B, section 7, lines 4830 through 5010). The adjustment factor for the momentum coefficient is the one-third power of the same ratio. Although these relations were found to agree well with the available data and represent the best approximations available, the simplifying assumptions required for their development should be recognized.

STABILITY LIMITS

In this discussion, it is assumed that the grass channel lining is used to protect an erodible soil boundary. Given this assumption, the stability limits of concern are those related to the prevention of channel degradation. Since significant bed load transport with its associated detachment and redeposition is incompatible with the maintenance of a quality grass cover, consideration may be further limited to particle or aggregate detachment processes. This limitation results in the logical dominant parameter being the boundary stress effective in generating a tractive force on detachable particles or aggregates.

For the soils most often encountered in practice, particle detachment begins at levels of total stress low enough to be withstood by the vegetation without significant damage to the individual vegetal elements. When this occurs, the vegetation is undercut and the weaker vegetation is removed. This removal decreases the density and uniformity of the cover, which in turn leads to greater stresses at the soil-water interface, resulting in an increased erosion rate. The progressively increasing erosion rate leading to unraveling of the lining is accentuated in supercritical flow by the tendency for slight boundary or cover discontinuities to cause flow and stress concentrations to develop.

For very erosion-resistant soils, the vegetal elements may sustain damage before the effective stress at the soil-water interface becomes large enough to detach soil particles or aggregates. Although the limiting condition in this case is the stress on the vegetal elements, failure progresses in much the same fashion. Damage to the vegetal cover results in an increase in effective stress on the soil boundary until conditions critical to erosion are exceeded. The ensuing erosion further weakens the cover, and unraveling occurs.

The potential for rapid unraveling of a channel lining once a weak point has developed, combined with the variability of vegetative covers, forces design criteria to be conservative. Very dense and uniform covers may withstand stresses substantially larger than those specified herein for short periods without significant damage. Reducing of the stability limits is not advised, however, unless a high level of maintenance guarantees that an unusually dense uniform cover will <u>always</u> exist. Also, unusually poor maintenance practices or nonuniform boundary conditions should be reflected in the design. (See chapter 3 for further discussions related to parameter estimation.)

Effective Soil Stress

The boundary stress effective in the detachment of soil particles is that associated with viscous drag on the soil boundary and pressure drag on soil particles or aggregates of a size that may be individually moved by the flow. Although it is convenient to think of this stress in terms of a time- and space-averaged stress associated with soil grain roughness, the temporal and spatial distribution of the stress is also important and is influenced directly by the presence of the vegetation. The computed erosionally effective boundary stress must, therefore, include consideration of this action.

Since Einstein (1950) introduced his sediment transport model that included a separation of form and grain roughness, numerous models and assumptions have been proposed for the separation of boundary stresses into components. Because of the complexity of the processes involved, none of the proposed approaches are analytically complete or exact. An approach that has proved effective for use in both nonvegetated (Taylor and Brooks 1962) and vegetated channels (Temple 1980) is to assume that, for a given discharge, the energy loss associated with a given component boundary roughness is an invariant function of the hydraulic radius. Under this assumption, the energy slope is divided into components as:

$$S = S' + S'' + S''' \tag{1.10}$$

where S' = the energy slope associated with the soil grain roughness,
S'' = the energy slope associated with boundary form roughness, and
S''' = the energy slope associated with the vegetal roughness or drag.

With the component roughnesses assumed to be expressed in terms of Manning's coefficients for each, and Manning's equation assumed to apply for each component, the total roughness is computed as the square root of the sum of the squares of the components (eq. 1.4). These same assumptions lead to S' being defined in terms of the component roughnesses as:

$$S' = S\,(n_s/n)^2 \tag{1.11}$$

Accounting for the fact that energy lost to the flow represents work done by a force acting on the moving water, the stress component separation is given by:

$$\tau = \gamma RS = \gamma RS' + \gamma RS'' + \gamma RS''' \tag{1.12}$$

in which τ is the gross mean boundary stress, γ is the unit weight of water, and the term involving S' is the mean boundary stress associated with the soil grain roughness. With n_s

considered to be a known property of the soil, the mean boundary stress associated with the soil may be computed.

The effect of the vegetation on the spatial and temporal distribution of the boundary stress is more difficult to determine on the basis of physical principles. Observations of flow behavior indicate that the characteristics of the cover most important in preventing local and/or temporary high stresses on the soil boundary are the cover density and, probably more important, uniformity of density in the immediate vicinity of the boundary. Since no adequate means is available for expressing these characteristics in terms of measurable parameters, Temple (1980) introduced an empirical vegetal cover factor for use in tractive stress design of grass-lined channels. Using this factor, the [erosionally] effective boundary stress for use in design is computed by the relation:

$$\tau_e = \gamma DS(1-C_F)(n_s/n)^2 \tag{1.13}$$

in which τ_e = the effective stress on the soil,
D = the maximum flow depth in the cross section,
C_F = the vegetal cover factor,

and the other variables are as previously defined. Examination of this relation shows the possible range of the cover factor to be between 0 and 1, where a value of 0 would imply no vegetal protection and a value of 1 would imply complete isolation of the soil boundary from stresses generated by the flow. Calibration of the cover factor using available vegetated channel stability test data resulted in a 0.5 to 0.9 range for the covers tested. For the relatively dense uniform covers tested, variations in cover density and uniformity of density are dominated by vegetal growth characteristics. Therefore, the cover factor is presented as a tabular function of vegetation type (table 3.1). Since this type of a tabular function cannot account for variations in maintenance practice and stand quality, judgment is required in the selection of this factor for a particular design.

The flow depth rather than the hydraulic radius is used in equation 1.13 because it is the maximum, rather than the average, stress which will initiate failure. The boundary stress correction factors suggested by Lane (1955) and reproduced by the SCS (1977) and others could probably be applied to the effective stress computed by equation 1.13 without significant error. The more conservative approach of ignoring this correction is advised, however, because of the distortion of the stress distribution that will result from the interaction of the vegetation with the flow and because of the tendency for a vegetative lining to unravel once damage has been initiated.

Allowable Effective Soil Stress

By definition, the allowable soil stress is the same for vegetated channels as for those unlined channels for which effective stress or tractive force is a suitable design parameter. For effective stress to be applicable as the sole stability parameter, detachment rather than sediment transport processes must dominate stability considerations. This means that sediment deposition and sediment transport as bed load must be negligible. As pointed out by Patronsky and Temple (1983), this is essentially the same restriction as must be applied to grass-lined channels if a quality cover is to be maintained.

Lane (1955) developed the tractive force approach for channel design in relatively coarse materials where stability usually implies satisfaction of the above restrictions and introduced the relation:

$$\tau_a = 0.4\ d_{75} \tag{1.14}$$

when:

$d_{75} > 0.25$ inch

where τ_a is the allowable stress in pounds per square foot, and d_{75} is the particle diameter in inches for which 75 percent of the material is finer. The Soil Conservation Service (SCS) (SCS 1977) uses this equation for the design of unlined channels in coarse noncohesive materials. The SCS procedure uses equation 1.13 (C_F = 0 for an unlined channel) to compute the effective stress, with the soil grain roughness determined by the relation (Lane 1955):

$$n_s = \frac{d_{75}^{1/6}}{39} \tag{1.15}$$

where d_{75} is again given in inches.

For fine-grained materials, application of tractive force or effective stress concepts to unlined channels is less straightforward because of the need to consider sediment transport and bed load particle redeposition processes. Attempts to use allowable stress or velocity as the primary design parameter have usually led to limiting conditions which are dependent on the sediment concentration in the flow as determined by sediment transport capacity and sediment supply considerations. The previously introduced bed-load limitation for vegetated channels means that the comparable condition for grass-lined and unlined channels is that specified as clear water or sediment free. This restriction also means that the bed forms normally present in unlined channels in fine noncohesive materials will not form in vegetated channels. Therefore, design limits dependent on their presence are not applicable to vegetated channels.

SCS (1977) presents both a permissible velocity and an allowable stress procedure applicable to the design of unlined channels in fine noncohesive material. The allowable stress procedure uses the mean particle diameter (d_{50}) as the variable determining allowable stress. The effective or "actual" stress is determined using a modification of Einstein's (1950) approach. Although the clear water allowable stresses appear reasonable for use with the grass-lined channel design procedure, the approach, as used by SCS, implies the presence of well-defined bed forms, making comparison to zero bed-load conditions questionable. Also, the use of d_{50} rather than d_{75} makes comparison of the fine-material allowable stress curves with equation 1.14 difficult.

The permissible velocity procedure is used for both cohesive and noncohesive fine-grained material. d_{75} is used as the primary soil parameter for noncohesive material, and the means of determining flow resistance is not specified. Since d_{75} is the same parameter used to determine the allowable effective stress for coarse material, the design limits may be directly compared by assuming a reference channel geometry and assuming equations 1.13 and 1.15 to apply to channels constructed in fine material. The results of such a comparison are shown in figure 1.2. Two reference channel geometries were used in the construction of this figure. The first was the conservative assumption of a straight wide channel (hydraulic radius equal to flow depth) having a flow depth of 3 ft. This assumption leads to a conversion relation given by:

$$\tau_a = 19.6\, V_a^2 n_s^2 \qquad (1.16)$$

where V_a is the permissible velocity and the other variables are as previously defined. The second is the less conservative channel geometry assumed by Lane (1955). Lane's stress distribution factors were also considered to apply in the construction of this curve. For the reasons previously discussed, only the permissible velocities applicable to "sediment-free" flows are shown in figure 1.2.

Examination of figure 1.2 in light of the variability of the parameters required for stable channel design suggests that for the bed-load limited condition applicable to grass-lined channels, equations 1.14 and 1.15 may be used for noncohesive material with grain sizes (d_{75}) greater than 0.05 inch. For grain sizes less than 0.05 inch, the soil grains are considered to be effectively submerged in the viscous sublayer of the flow with the grain roughness and allowable effective stress both considered to remain constant at limiting values of n_s=0.0156 and τ_a =0.02 lb/ft^2.

Possibly because of the variability of material properties and the complexities of the interaction of the flow with boundary sediments in the form of bed material transport, allowable stress has not been widely used for the design of channels in cohesive materials. The SCS (1977) offers on1y a permissible velocity procedure for stability design of channels in cohesive materials. The soil parameters used to determine the permissible velocity are the soil's classification in the unified soil classification system, its plasticity index, and its void ratio. In applying the procedure, a basic permissible velocity is first obtained from the soil's classification and its plasticity index. This basic velocity for the material is then multiplied by a correction factor that is a function of soil classification and void ratio.

In converting the SCS (1977) criteria to an effective stress format, it is convenient to convert the basic velocities directly using equation 1.163 and adjust the resulting allowable stress by the square of the void ratio correction factor used by scs. Since n_s is by definition the soil grain roughness associated with particles or aggregates of a size capable of being detached by the flow, equation 1.16 may be applied with an n_s value of 0.0156 to convert these permissible velocities to values of allowable effective stress if it is assumed that erosion of these materials is primarily through detachment of particles or aggregates with diameters less than 0.05 inch. The effective stresses equivalent to the SCS (1977) permissible velocities obtained for cohesive materials using this approach are presented in both graphical and numerical formats in chapter 3 (tables 3.3, figures 3.1 through 3.4). With the limiting conditions expressed in this fashion, the design procedure for grass-lined channels is independent of soil type, providing the

[3]The selection of the more conservative channel geometry leading to equation 1.16 is considered to be in line with the high degree of uncertainty Involved in determining the erodibility of cohesive soils.

vegetal limitations are observed. The procedure is also applicable to the design of unlined channels for which the zero bed-load transport limitation is reasonable.

Limiting Vegetal Stress

Because the failure most often observed in the field and in the laboratory has resulted from the weakening of the vegetal lining by removal of soil through the lining, few data exist related to the maximum stresses that vegetal elements rooted in highly erosion-resistant materials may withstand. Observations of cover damage under high stress conditions (Ree and Palmer 1949), however, indicate that this type of failure may become dominant when the vegetation is established on highly erosion-resistant soils. These observations also indicate that when vegetal failure occurs, it is a complex process involving removing young and weak plants, shredding and tearing of leaves, and fatigue weakening of stems. The complexity of this process combined with limited data force the stability limitation developed below to be only a rough approximation. A more detailed treatment would require the inclusion of many additional variables, not normally available in the design situation, to adequately describe both the soil and the cover. The use of an approximating relation, therefore, is considered appropriate for most practical applications.

For conditions where the soil surface remains intact, the dominant action associated with vegetal cover failure appears to be fatigue-related stem breakage combined with leaf damage and removal. Force is transmitted from the flow to a vegetated boundary by drag along the entire length of a submerged vegetal element. This distribution of force along the stem, coupled with the fact that the waving action of longer stems will be at a lower frequency, and with the increased size and maturity [usually] associated with greater stem length, suggests that the allowable boundary stress associated with the vegetation should increase with stem length and density. An approach consistent with these considerations and with the limited data available on vegetal failure is to assume that the allowable vegetal stress is directly proportional to the retardance curve index. Using the available data to estimate the proportionality constant results in:

$$\tau_{va} = 0.75\ C_I \tag{1.17}$$

in which τ_{VA} is the maximum allowable stress on the vegetation in pounds per square feet and C_I is the previously defined retardance curve index.

To be consistent with the discussion in the previous section, the vegetal stress, τ_v, for a given flow condition would be computed as the gross boundary stress adjusted by the square of the ratio of the vegetal roughness coefficient to the total roughness coefficient. Because of the limited data available, the usual dominance of vegetal resistance, and the simplifying assumptions required for vegetal roughness computation, equation 1.17 was developed under the assumption that:

$$\tau_v = \tau - \tau_e \tag{1.18}$$

This approach is more computationally convenient in that no new parameters are required for the vegetal stability check.

ADDITIONAL CONSIDERATIONS

The relations discussed previously are those which are necessary for any grass-lined channel stability design application and/or are unique to the use of grass as a channel lining. For clarity of presentation, the relations are generally developed in the context of steady uniform flow in a prismatic channel. Therefore, this presentation cannot be used as the sole reference for all design problems involving grass-lined channels. An attractive point of the effective stress approach to design, however, is that such problems as Froude number, water surface stability checks, and curvature super elevation computations, may be handled using the same procedures for both lined and unlined channels.

Although the same relations are used for both lined and unlined channels, engineering judgment remains an essential part of the design process, and certain cautions must be observed. Most relations used in open channel design are based on the conservation of mass, energy, and/or momentum. In many instances, the most familiar form of a relation is one that has been simplified by the assumption of momentum and energy coefficients equal to unity. Because this is not always an acceptable assumption for a grass-lined channel, however, the familiar procedures or relations should be re-examined and the appropriate coefficients included prior to their application to conditions involving grass linings.

Engineering judgment is also essential to determine the influence of maintenance practices on design parameters. For example, regular mowing of a turfqrass cover over a well-prepared soil bed may significantly increase vegetal density and uniformity, resulting in an increased value of the vegetal cover factor appropriate for the lining. Conversely, untimely cover removal from a soil surface containing significant discontinuities may leave the soil more open to local erosive attack.

Under supercritical flow conditions, relatively minor discontinuities in flow resistance and/or elevation may cause significant flow and stress concentrations. And extreme discontinuities such as animal or vehicular trails paralleling the flow may negate the protective benefits of the vegetal lining. Appropriate care should therefore be exercised in the development of maintenance programs for this type of channel.

Table 1.1
Curve fit coefficient matrix for use in the computation of the energy coefficient α

i \ j	0	1	2	3
0	4.31	-9.19	1.99	1.57
1	.230	-.0216	.178	-.000932
2	-.0177	.00857	.00159	.00364
3	-.000155	.000815	-.00114	-.000283
4	.0298	.0833	.00796	-.000359

Table 1.2
Curve fit coefficient matrix for use in the computation of the momentum coefficient β

i \ j	0	1	2	3
0	2.93	-7.68	0.800	1.54
1	.0888	.152	.223	-.035
2	-.0000729	.0220	.00518	.00845
3	-.000669	-.00226	-.00146	-.00053
4	.0146	.0828	.0263	-.00304

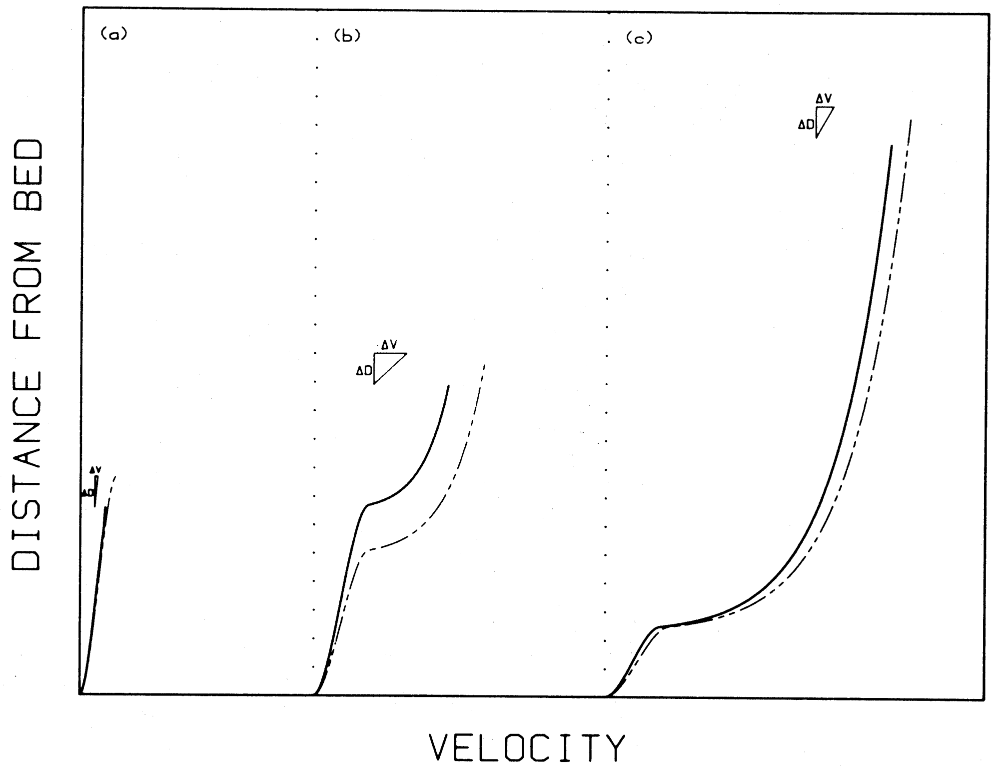

Figure 1.1
Velocity profile sketch illustrating the effect of an increase in flow depth on velocity in (a) the low-flow region, (b) the intermediate-flow region, and (c) the high-flow region.

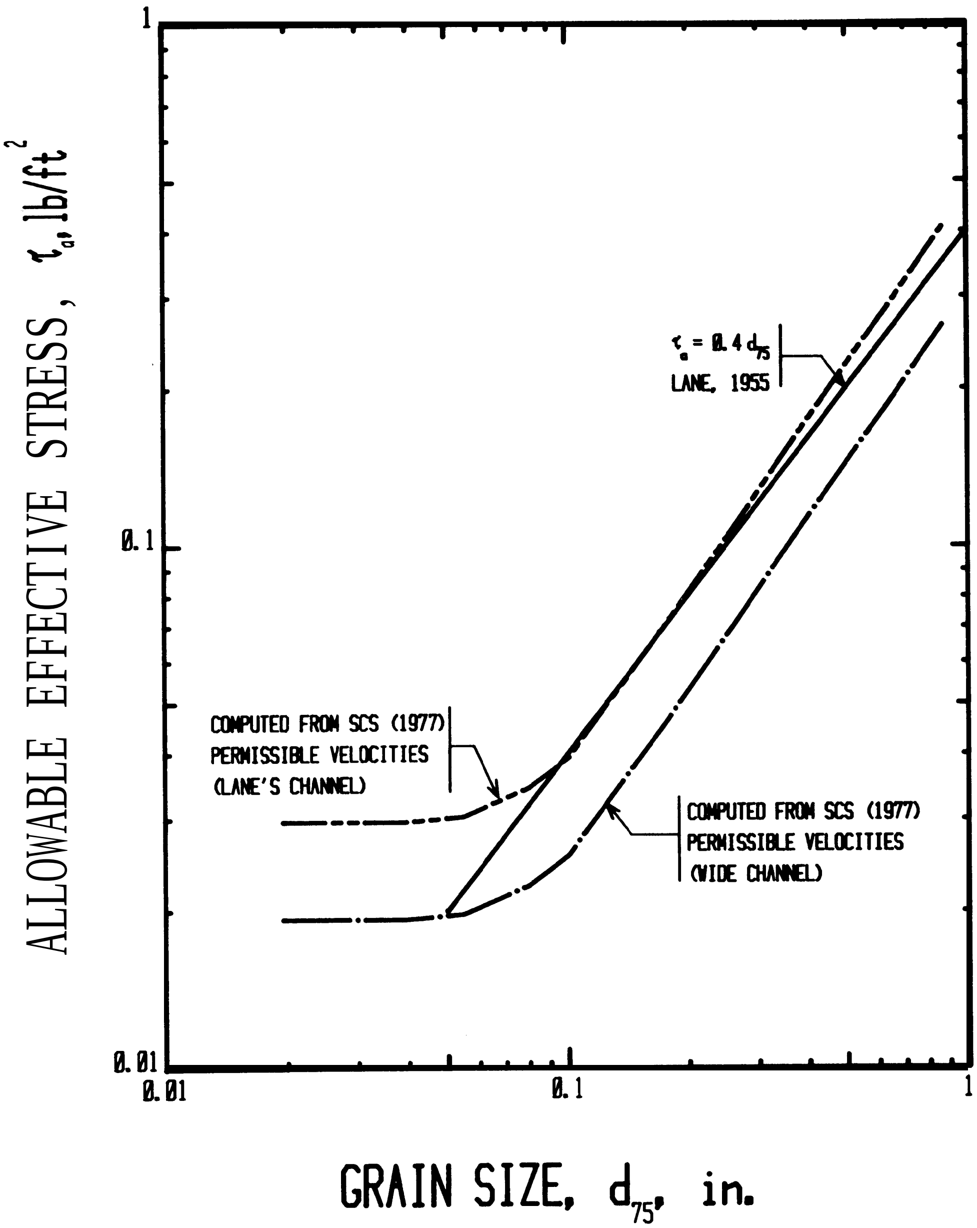

Figure 1.2
Comparison of Lane's (1955) allowable stress stability criteria with the SCS (1977) criteria for sediment-free flow over the same material

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